TIME-RESOLVED VOLTAGE MEASUREMENTS OF IMPLODING RADIATION SOURCES AT 6 MA WITH A VACUUM VOLTMETER *

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Abstract

A vacuum-voltmeter[1] (VVM) was fielded on the Saturn pulsed-power generator during a series of 12-MA short-circuit, 6-MA aluminum wire-array z-pinch, and 6 MA argon Plasma Radiation Source (PRS) shots. The VVM was connected to the convolute structure in the vacuum chamber above the load. This arrangement permitted the VVM to directly measure the time-resolved voltage between the ground side of the magnetically insulated transmission line (MITL) anode and the negative high-voltage cathode feed to the load. The time-resolved voltage and the separately-measured load current are used to determine several dynamic properties during the wire or gas-puff load implosion, namely, the inductance, *L(t)*, coupled energy delivered to the load, $E_{coupled}(t)$, and the load radius, *r(t)*.

We report here the results of these tests for a fixed inductance short-circuit load and a 12-cm diameter, argon gas-puff load. We correlate the time dependent electrical parameters with the radiation output from the imploding loads. In particular, we observe electrical energy being delivered to the pinch during and after the radiation pulse.[2][3]

I. INTRODUCTION

The SATURN pulsed power machine[4] is driven by 36 marx-generator modules arranged in a circle, feeding a multi-layer MITL at the hub of the circle. A posthole convolute[5] is used to drive plasma radiation sources such as imploding wire arrays or imploding gaseous structures. In high-voltage, high-current machines like Saturn, independently-calibrated, load-current diagnostics are routinely mounted in the ground electrode close to the diode. Voltage measurements are usually made several meters away on the water side of the water-vacuum interface. The load voltage is then estimated from the interface voltage and a circuit analysis of the MITL and the diode. Any current loss in the transmission lines or convolute structure must be accounted for in the estimate of the load voltage. Saturn's MITL setup for z-pinch shots allows access to the high voltage electrode from inside the vacuum chamber above the diode. Mounting a voltage diagnostic directly on the high-voltage side of the diode allows a direct determination of the load voltage. With separately measured current and voltage at the load, one can determine the inductance, the radius of the pinch and the energy coupled into the load.

II. DATA ANALYSIS

In a typical z-pinch load (see Fig. 1) there is a fixed pinch length, *l*, a fixed outer conductor radius, *b*, an initial radius, r_0, and an imploding pinch radius, *r(t)*.

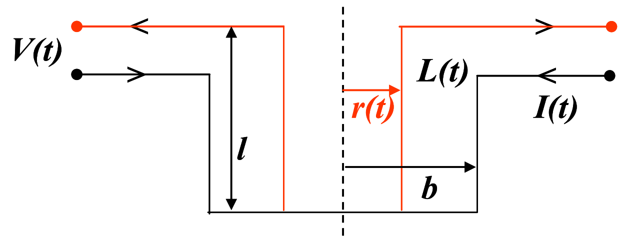

Figure 1 The inductance of the system includes the inductance of the pinch region and the inductance of the current feeds.

The inductance of the load region is determined from the load current and load voltage measurements by Eq. (1). The inductance between the voltage measurement position and the axis is the integral of the load voltage divided by the load current, assuming negligible resistance.

$$L(t) = \frac{\int_0^t V(t')dt'}{I(t)} \quad (1)$$

The change in the average current radius is determined from the change in the inductance, as shown in Eq. (2) and Eq. (3). Here *b*, *l* and *r* are in cm, $\mu_0 = 4\pi 10^{-7}$ H/m.

$$\begin{aligned}\Delta L &= L(t) - L_0 \\ &= \frac{\mu_0 \cdot l}{2\pi} \cdot \left[\ln\left(\frac{b}{r(t)}\right) - \ln\left(\frac{b}{r_0}\right) \right] \\ &= 2 \cdot l \cdot \left[\ln\left(\frac{r_0}{r(t)}\right) \right] \text{ (nH)}\end{aligned} \quad (2)$$

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$$r(t) = \frac{r_0}{\exp\left(\frac{\Delta L}{2 \cdot l}\right)} \quad (3)$$

The energy coupled into the pinch is the total input electrical energy minus the energy contained in the magnetic field outside the pinch, as shown in Eq. (4).

$$E_{coupled}(t) = \int_0^t IVdt' - \frac{1}{2} LI^2 \quad (4)$$

Eq. (4) can be rewritten in terms of the derivative of the inductance, as shown in Eq. (5).

$$E_{coupled}(t) = \frac{1}{2} \int_0^t I^2 \left(\frac{dL}{dt'} \right) dt' \quad (5)$$

III. EXPERIMENTAL PROCESS

The VVM was fielded on two series of Saturn shots in early 2006. The first series (shots 3549-3555) used short-circuit and wire array load shots. The second series (shots 3562-3565) used plasma-radiation-source (PRS), argon gas-puff load shots. The gas plenum and valve system for the L3 Communications built, 12-cm diameter gas-puff nozzle extends from the high voltage cathode about 50 cm into the vacuum region above the diode. A similarly sized aluminum cylinder was attached to the wire-array load hardware to mock-up the gas-puff system. Fig. 2 is a photo of the VVM mounted in the MITL and attached to the cylinder by a flexible strap. Fig. 3 is a schematic of the MITL hardware and the placement of the VVM.

A. Wire Array Hardware

The first shot (#3549) was into a short circuit with the same length and diameter as the subsequent wire-array shots. Unfortunately, the mechanical shock from the 12 MA current pulse into the short circuit load launched the aluminum cylinder upward with sufficient force that the strap connecting it to the VVM sheared off and the cylinder hit the VVM. This caused internal damage to the VVM which rendered the data for shots 3550-3555 unreliable. The VVM was repaired before the second series of shots with the gas-puff hardware.

The data from the short-circuit shot #3549 is shown in Fig. 4. The red curve is the load voltage as measured by the VVM. The blue curve is the load current as measured by B-dot loops mounted in the ground electrode. The magenta curve is the integral of the VVM signal. The ratio of the integrated voltage and the current is the inductance, which is shown in green. The short circuit was a thick-walled aluminum cylinder which did not

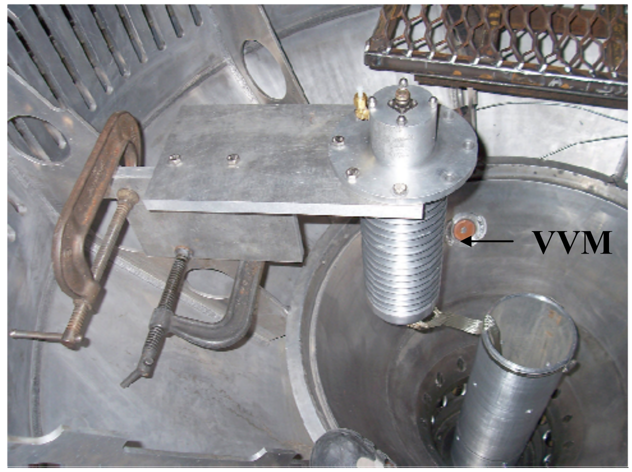

Figure 2 The VVM is mounted inside the MITL, above the load region. A strap connects the input of the VVM to an aluminum cylinder that approximates the dimensions of the gas-puff hardware for the PRS series of shots.

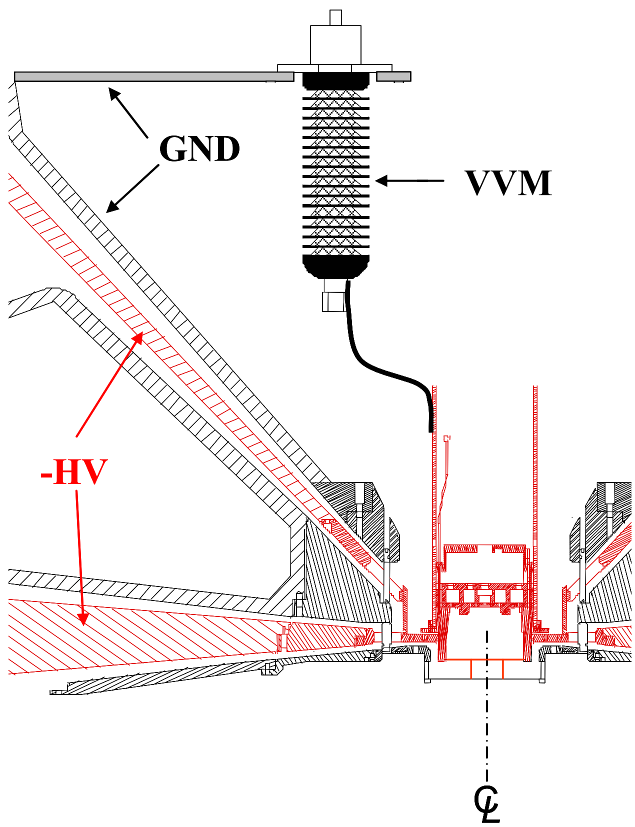

Figure 3. A schematic of the MITL structure and the placement of the VVM.

move on the timescale of this graph, so the inductance trace is constant during the current pulse. The system inductance includes the electrical feeds from the MITL convolute structure inward and the short-circuit hardware. Based on mechanical drawings of the diode region, the inductance was estimated to be 5.85 nH. The measured inductance was 5.75 nH. The peak diode voltage was

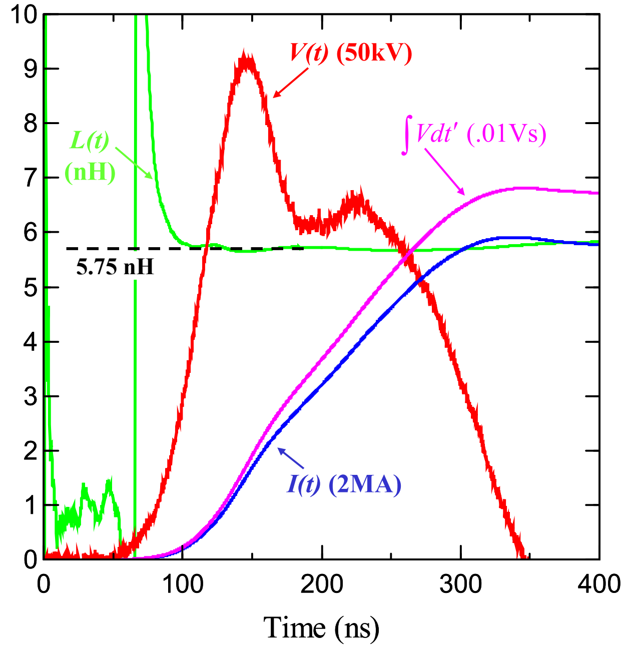

Figure 4. The short circuit load parameters are l=4 cm, b=2.5 cm and r_0=2 cm. The scale units for the traces are 1 nH/div, 50 kV/div, 2 MA/div and .01 Vs/div.

450 kV and the peak current was 12 MA. Saturn was operated in its long pulse (200 ns) mode. The integral of the voltage signal is exactly proportional to the current signal, as expected for a fixed inductance.

B. Gas-Puff Hardware

Fig. 5 shows details of the 12-cm diameter injector used for the argon gas-puff shots. It has a 1 cm diameter central jet and two, 1 cm wide, concentric nozzles. The outer radius of the outer nozzle is 6 cm. The gas passes through two wire meshes, spaced 3.8 cm apart. The first mesh is attached to the face of the nozzle and is at the same voltage as the nozzle. The second mesh is attached

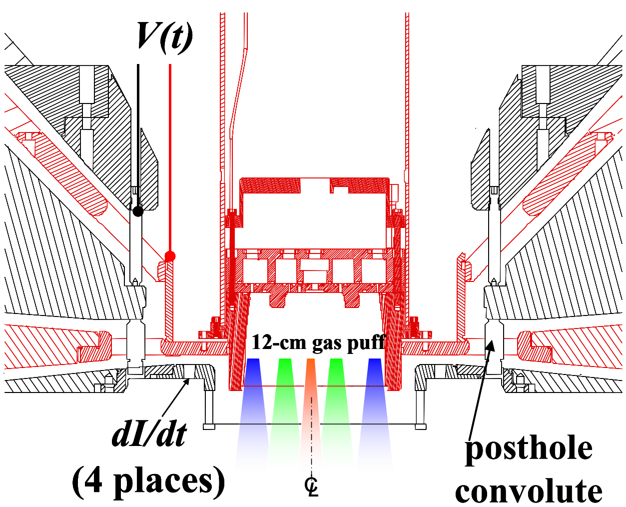

Figure 5. Schematic of the gas-puff diode hardware. Areas in red are at high voltage. Areas in black are grounded. The VVM is attached to the high voltage side.

to grounded, return-current posts. The inner radius of the return current posts is 8.6 cm. The pressures at the jet and the two nozzles are independently adjusted to produce a radially decreasing density profile, i.e., the density is highest on axis. Four B-dot probes are mounted symmetrically in the ground side electrode to measure the load current. The nozzle, wire meshes and B-dot probes are all replaced after each shot.

The injector system was fed by power, signal cables and gas lines connected to the injector through a coiled inductive isolator. A flexible, braided wire section of the connection comes to the same voltage as the injector during the shot. The VVM insulator stack flashed over during the several of the gas-puff shots even though the applied voltage was below the design hold-off voltage of the instrument (2 MV). The flash-over was likely caused by electrons, emitted from the braided connection to the isolator, depositing on the insulator stack. The problem was mitigated by shielding the VVM insulator stack with a metal cylinder (see Figs. 6&7).

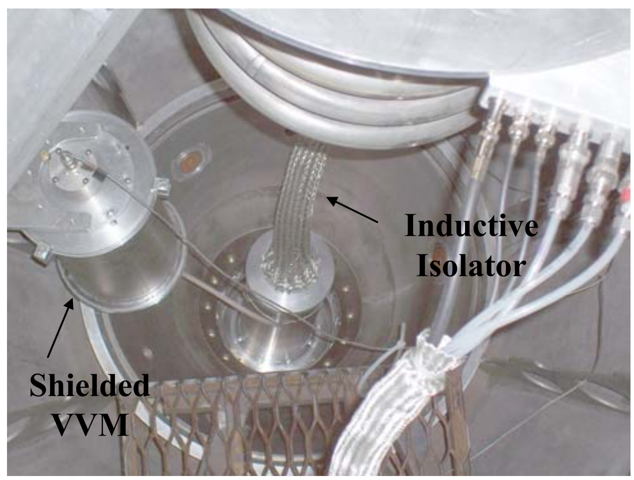

Figure 6. Photograph of the diagnostic arrangement for the last gas-puff shot. A braided wire section connects the injector and the inductive isolator. A metal shield has been placed over the VVM.

C. Gas Puff Shot Data Analysis

The data from gas-puff shot #3565 are shown in Fig. 8. The VVM voltage signal is in red and peaks at about 1.2 MV. The current trace peaks at 6.5 MA and is dark blue. The inductance, calculated from the current and voltage, is shown in green. It is 4.4 nH initially and rises to 39 nH by the end of the radiation pulse. The axially-averaged current radius, calculated using Eq. (3), is in black. The initial radius is 8.3 cm, just inside the 8.6 cm inner radius of the return current posts. The gas expands to fill the volume bounded by the wire meshes and the return-current posts. During most of the current pulse, the radial velocity is constant at about 0.46 mm/ns. The current sheath is moving into increasingly higher density

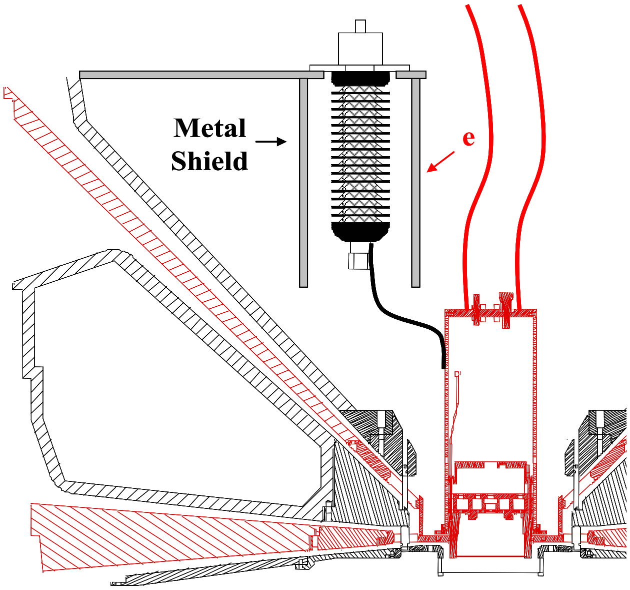

Figure 7. Schematic of the gas-puff hardware with the braided wire section that connects the injector to the inductive isolator. The metal shield prevents stray electrons causing the VVM insulator stack to flashover.

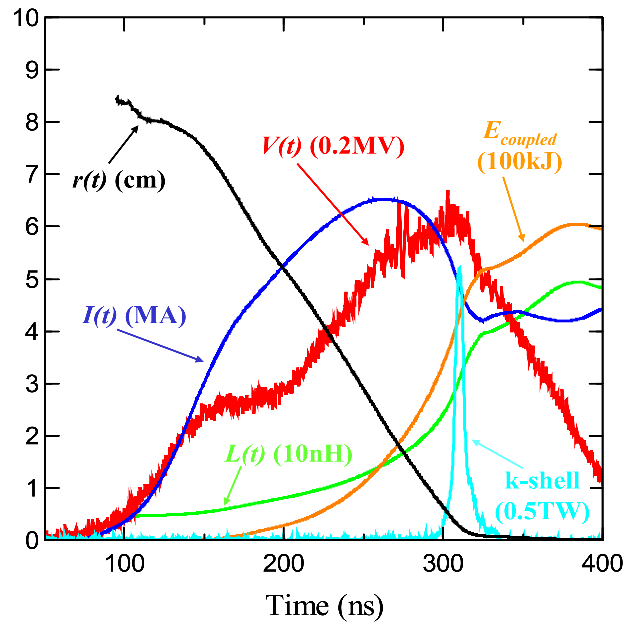

Figure 8. Saturn gas-puff shot 3565 data. The scale units for the traces are 1 MA/div, 0.2 MV/div, 10 nH/div, 1 cm/div, 100 kJ/div and 0.5 TW/div.

gas. The velocity slows as the density and temperature of the swept-up gas become sufficient for the plasma to produce k-shell radiation. The time-integrated, k-shell yield was 72 kJ on this shot, which was about half that of the electrical energy increase during the k-shell pulse. Approximately 510 kJ of electrical energy was coupled into the pinch from the start of the discharge to the end of the k-shell pulse. Electrical energy was still being fed into the plasma after peak compression. See the paper by R. J. Commisso, et al., "Long-Implosion-Time, 12-cm-Diameter Argon-Gas-Puff Experiments at ~ 6 MA" in this Proceedings for further discussion of the energy balance.

IV. CONCLUSIONS

When adequately shielded, a VVM can make direct load voltage measurements on Saturn z-pinches with fixed inductance loads, imploding wire array loads and with gas-puff loads. Independently measured voltage and current allow the calculation of the net electrical energy coupled into the load. We have proposed adding the VVM to the diagnostic suite in future gas-puff experiments on Saturn and Z.

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